DHI

Development of Mechanistic Models

Mechanistic Model for Nissum Fjord

Hydrodynamic model documentation

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Mechanistic Model for Nissum Fjord

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The model development presented in this technical note represents the hydrodynamic model development for Nissum Fjord. The Nissum Fjord model is a part of a larger model complex comprising a number of mechanistic models developed by DHI and a number of statistical models developed by Aarhus University (AU), Bioscience.

The model complex is developed with the overall aim to support the Water Framework Directive (WFD) by introducing mechanistic models in as many Danish water bodies as possible, and to integrate with Bayesian statistical modelling and cross system modelling carried out by AU, Bioscience.

Here we present the hydrodynamic (HD) model setup covering Nissum Fjord. This specific model includes three Danish water bodies:

Water Body*)	Number
Nissum Fjord, ydre	129
Nissum Fjord, mellem	130
Nissum Fjord, Felsted Kog	131

*) Water bodies defined for the River Basin Management Plans 2015-2021.

The Nissum Fjord hydrodynamic model is developed to describe the physical system (water levels, currents, turbulence, mixing, salinity and water temperature). The model is developed to ensure a quality that will support a robust ecosystem (biogeochemical) model, an ecosystem model that can be used eventually for modelling a number of scenarios in support of the WFD implementation in Denmark.

As can be seen from the present technical note the Nissum Fjord hydrodynamic model was developed successfully for the entire model period 2002-2016:

- On average the P-Bias is -1.4% with respect to salinity and -6.9% with respect to water temperature. Hence, on average the model meets a model performance of 'excellent' for both salinity and temperature, which is also the case for the individual stations.

- With respect to the Spearman Rank Correlation the average numbers are 0.73 and 0.97, respectively, for salinity and water temperature. This means that the average model performance (and the individual stations) at the two stations used for validation meets 'very good' and 'excellent' for salinity and water temperature, respectively.

- The average Modelling Efficient Factor (MEF) for salinity is 0.43 corresponding to a 'good' model, which is also the case for the two individual stations. For both stations the modelled levels are correct and overall variability seems correct, which is also highlighted by the two other measures P-Bias and Spearman Rank Correlation. However, the timing of certain events is not entirely correct which is why the MEF is not evaluated as 'excellent' or 'very good'. With respect to water temperature the values are 0.90 and 0.89 corresponding to an 'excellent' model.

The details behind the above data are available in Table 6.1 and Table 6.2 and time series comparisons are available here: rbmp2021-2027.dhigroup.com (Google Chrome only).

Based on the two tables and the time series (the time series are available at rbmp2021-2027.dhigroup.com) we conclude that the model describes the overall physical features in Nissum Fjord and that the model is adequate for ecosystem model development.

2 Introduction

The model development presented in this technical note represents the hydrodynamic model development for Nissum Fjord. The Nissum Fjord model is a part of a larger model complex comprising a number of mechanistic models developed by DHI and a number of statistical models developed by AU, Bioscience.

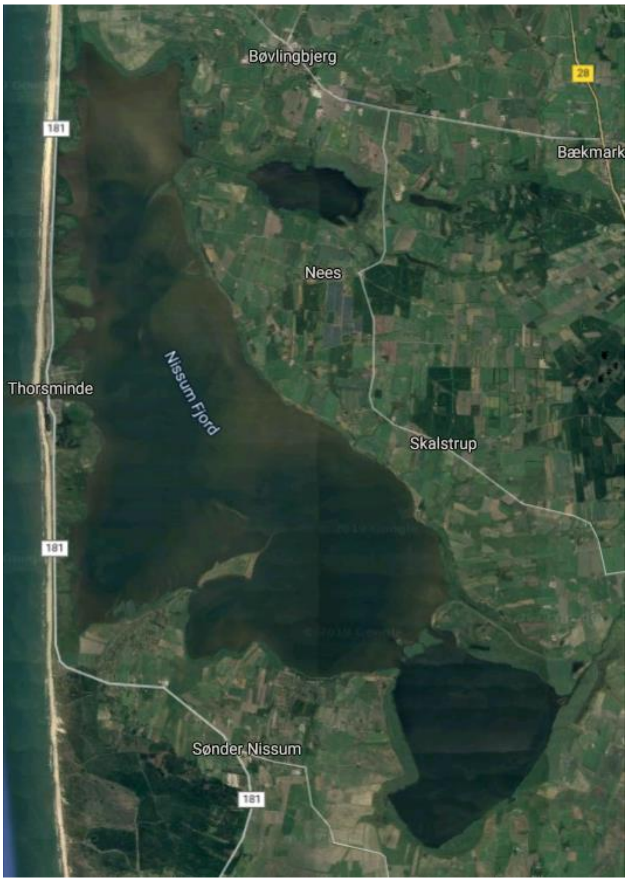
The model complex is developed with the overall aim to support the Water Framework Directive (WFD) by introducing mechanistic models in as many Danish water bodies as possible, and to integrate with Bayesian statistical modelling and cross system modelling carried out by AU, Bioscience.

Here we present the hydrodynamic (HD) model setup covering Nissum Fjord. This specific model includes three Danish water bodies (see Table 2.1) and the water bodies are shown in Figure 2.1.

Table 2.1 Water bodies included in the Nissum Fjord model

Water Body*)	Number
Nissum Fjord, ydre	129
Nissum Fjord, mellem	130
Nissum Fjord, Felsted Kog	131

*) Water bodies defined for the River Basin Management Plans 2015-2021.



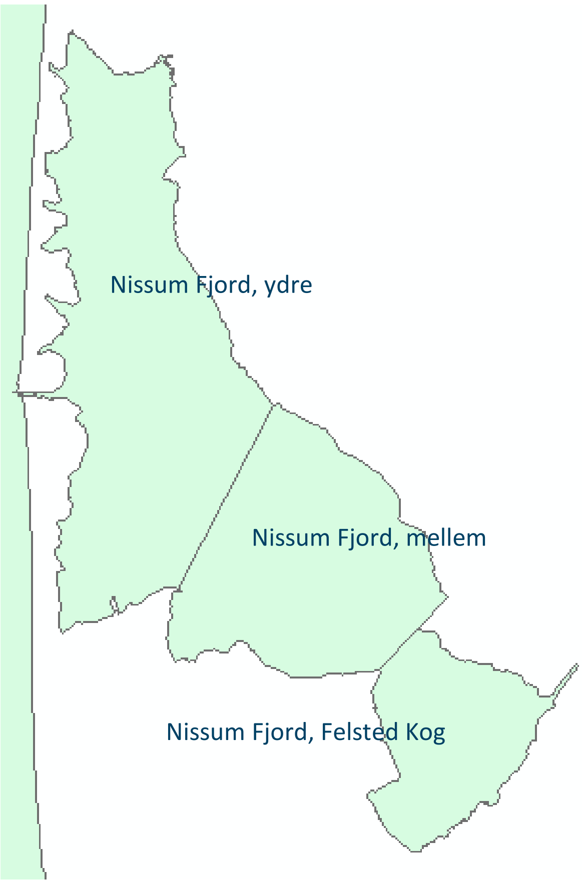


Figure 2.1 (Left) Nissum Fjord (from Google Maps) and (right) the different water bodies included in the Nissum Fjord model.

3 Modelling Concept

3.1 Mechanistic Modelling

The present technical note represents the hydrodynamic part of one model out of eleven mechanistic models. The eleven mechanistic models are developed to increase the knowledge of pressures and status in Danish marine waters and to provide tools for the Danish EPA as part of the implementation of the WFD.

Mechanistic models enable dynamic descriptions of ecosystems and interactions between natural forcings and anthropogenic pressures. Hence, mechanistic models can be applied for predictions of changes in specific components, like chlorophyll-a concentrations, due to climatic changes or changes in anthropogenic pressures.

The ecological conditions in marine waters are determined by a number of different natural factors like water exchange, stratification, water temperature, nutrient availability, sediment characteristics, structure of the food web, etc. In addition to that numerous anthropogenic factors, like nutrient loadings, fishery, etc., also impact the ecosystem and potentially the ecological status.

The model development in this specific project aims at supporting the Danish Environmental Protection Agency's (EPA) implementation of the WFD. In this first phase of the model development the models are developed to represent the present period (2002-2016) evaluated against NOVANA measurements. Here we use present meteorological data, present nutrient loadings, etc.

After the models are finalized, they will be applied for scenario modelling, although the specific scenarios are not yet defined.

3.2 Model Development

The model development consists of a 3D hydrodynamic model describing the physical system; water levels, current, salinity and water temperatures. Following the development of the hydrodynamic model is the development of the biogeochemical (ecosystem) model describing the governing biogeochemical pelagic and benthic parameters and processes like phytoplankton, dissolved oxygen, primary production, etc. The model structure is modular, meaning that a hydrodynamic model is developed independently of the biogeochemical model.

The Nissum Fjord model is defined as an estuary specific model. The mechanistic model complex developed as part of the present projects includes two regional models, three local-domain models and six estuary specific models.

- Regional models: Regional models cover both specific Danish water bodies and regional waters, such as the North Sea and a small part of the North Atlantic, which is included in the North Sea-model and the Baltic Sea, which is covered by the IDW-model (Inner Danish Waters). These models provide model results for specific water bodies but, equally important, provide boundaries to local-domain models and estuary specific models.

- Local-domain models: These models are developed to allow for resolving the majority of small and medium-sized water bodies in the north-western Belt Sea, the south-western Belt Sea and the waters bodies in and around Smålandsfarvandet.

- Estuary specific models: Six specific estuary (fjord) models are developed to allow for detailed modelling of the particular estuary.

All mechanistic models will be set up and calibrated for the period 2002-2010 and validated for the period 2011-2016. In this note the validation will be reported according to specific indices (DHI 2019a), whereas the entire period is included as time series in a WEB-tool (rbmp2021-2027.dhigroup.com) with a few examples included in 6.2.2. Most data used for calibration and validation originate from the national monitoring programme NOVANA, see http://odaforalle.au.dk for more details. For some models and some parameters other data are included, and the specific origin of those data will be referenced when used.

3.3 Modelling System

The hydrodynamic model is based on the modelling software MIKE 3 HD FM (version 2017) developed by DHI. MIKE 3 HD FM is based on a flexible mesh approach and was developed for applications within oceanographic, coastal and estuarine environments.

The system is based on the numerical solution of the three-dimensional (3D) incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme. The free surface is considered using a sigma-coordinate transformation approach. The scientific documentation of MIKE 3 HD FM is given in DHI (2017a).

4 Model Setup

4.1 Introduction

The model setup comprises defining the model domain, establishing the model mesh, preparing the model forcings in terms of open boundary conditions, atmospheric forcing and freshwater inflows, preparing the initial conditions and setting up the model.

For the present project the model is set up for the period 2002-2016, which means that all model forcings need to cover this period.

4.2 Model Domain

4.2.1 Introduction

The model domain is determined in accordance with the area of interest of the modelling study. Also, considerations of the area of influence, being the surrounding areas that affect the area of interest, and of suitable open boundary locations, affect the choice of model domain.

For the Nissum Fjord model, it was chosen to model the fjord as a 'lake' with closed boundaries. Thus, the freshwater runoff from land and the seawater exchange through the sluice were modelled as point sources.

The model mesh is the representation of the model domain. More specifically the model mesh defines the model area, the location of the open boundaries, the land-water boundaries, the horizontal and vertical model resolution (discretization), and the water depths (bathymetry) of the model. In the following sections the details of the horizontal and vertical model mesh are described.

4.2.2 Horizontal Mesh

The horizontal mesh is unstructured and generally composed of triangular elements but may also include quadrangular elements. For the Nissum Fjord model the horizontal mesh consists exclusively of triangular elements, with a mesh resolution in the range of 150 m – 250 m between element centres. Figure 4.1 (left) shows the mesh with a map projection given by ETRS-1989-UTM-32. The model bathymetry shown on Figure 4.1(right) is based on satellite derived bathymetry data by GRAS (DHI (2019b)). The vertical datum of the bathymetry is DVR90.

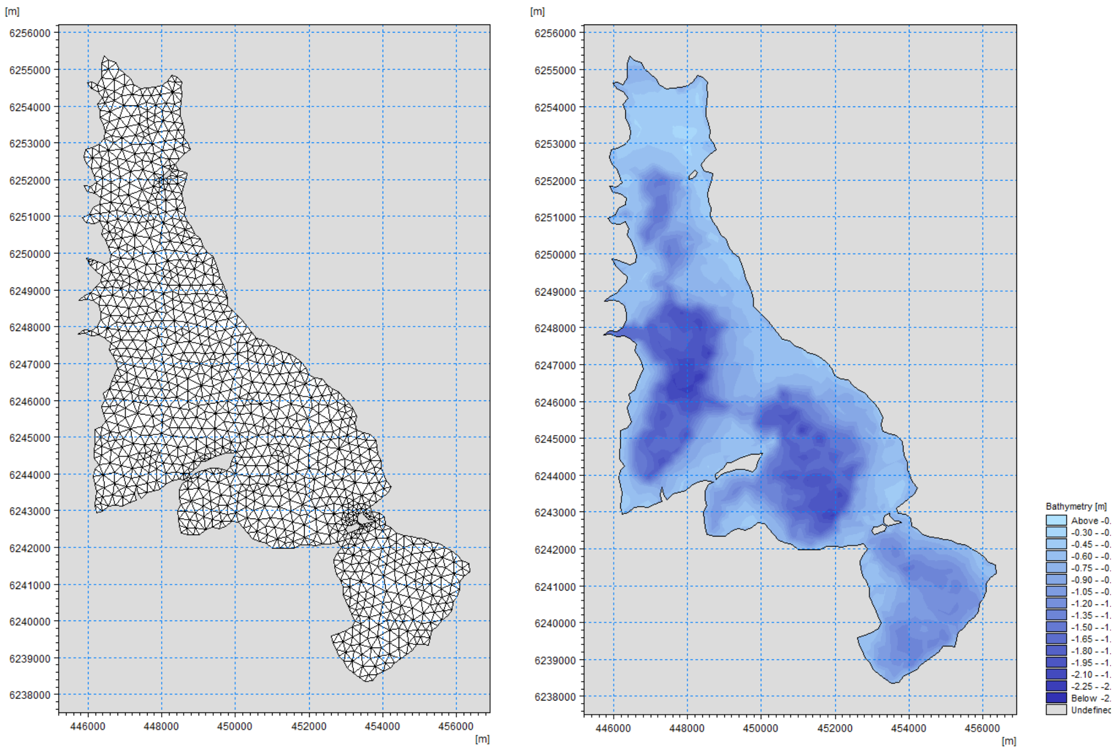


Figure 4.1 (Left) horizontal mesh and (right) bathymetry of the Nissum Fjord model. Map projection ETRS-1989-UTM-32 and vertical datum DVR90.

4.2.3 Vertical Mesh

The vertical mesh is structured and consists of either sigma-layers or a combination of sigma- and z-layers. In the Nissum Fjord model, 10 sigma-layers were used with refinements towards the water surface and the fjord bed. Figure 4.2 shows the ratio between each sigma-layer thickness and the water depth. This ensures that at the deepest location of approximately 2.5 m, the mid-layers are up to 0.5 m thick, while the bottom and surface layers are 0.1 m thick. Figure 4.3 illustrates the vertical mesh.

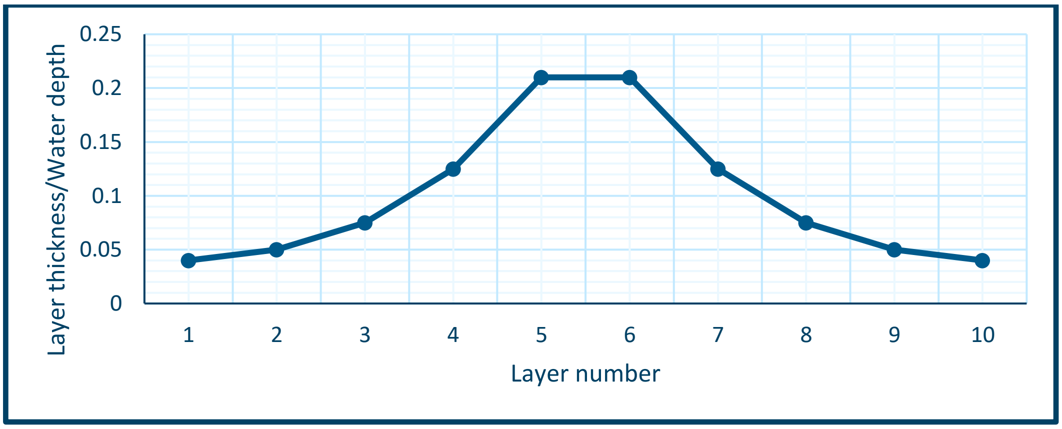


Figure 4.2 Ratio of sigma-layer thickness to water depth, as function of the layer number.

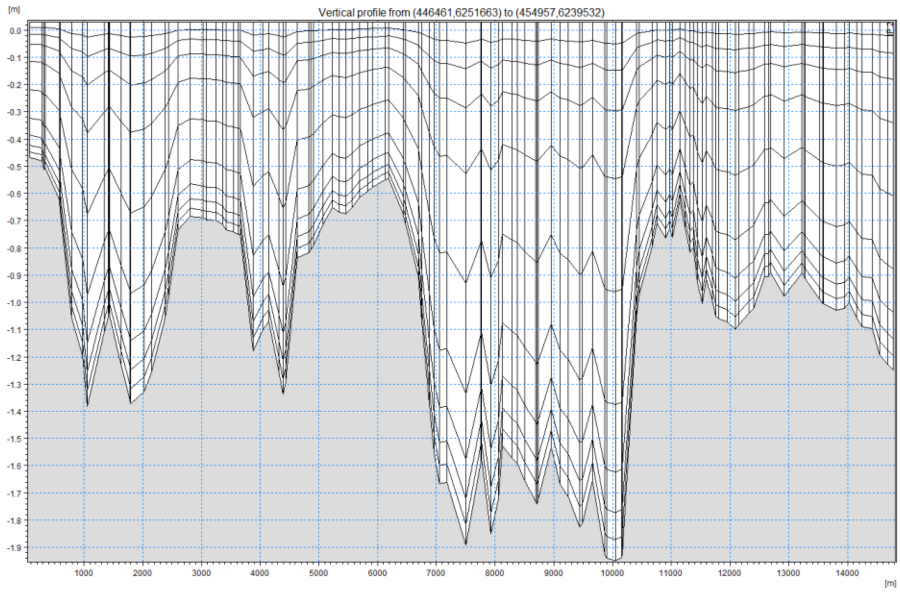


Figure 4.3 Vertical model mesh of the Nissum Fjord model in transect from North-West to South-East, with 10 sigma-layers refined towards the surface and fjord bed.

4.3 Model Forcings

4.3.1 Open Boundary Conditions

No open boundaries are used in the model. The water exchange between the fjord and the sea is modelled with source terms as described in in section 4.3.3 below.

4.3.2 Atmospheric Forcing

The atmospheric forcing of the Nissum Fjord model is provided by StormGeo in terms of temporally and spatially varying fields of:

- Wind
- Atmospheric pressure
- Precipitation
- Air temperature
- Relative humidity
- Cloud cover

The applied atmospheric data are from StormGeo's WRF meteorological model covering the North Atlantic. The data are provided in a resolution of 0.1° x 0.1° in hourly time-steps.

The StormGeo data are only available from 2009 and onwards. Therefore, meteorological fields from Vejr2 of Denmark (0.15°, hourly) were applied for the period 2005-2009 and meteorological fields from Climate Forecast System Reanalysis (CFSR) (0.3-0.5°, hourly) were applied for the period 2002-2005.

4.3.3 Freshwater Sources

The Nissum Fjord model includes a number of model sources representing the freshwater run-off from land to fjord. For each of the three water bodies shown in Figure 4.4 (129, 130, 131) a total daily discharge time series is available based on data from DCE (Aarhus University) -

Denmark. In order to get a natural distribution of the freshwater inflow, point sources were added around each water body with the following subdivision:

- Water body 129: The south-easternmost source weighed 1/2, and the rest of the sources weighed 1/4 each, of the area discharge.
- Water body 130: The eastern source weighed 9/10, and the western source weighed 1/10 of the area discharge.
- Water body 131: The north-easternmost source (Storå) weighed 4/5, and the rest of the sources weighed 1/20 each, of the area discharge.

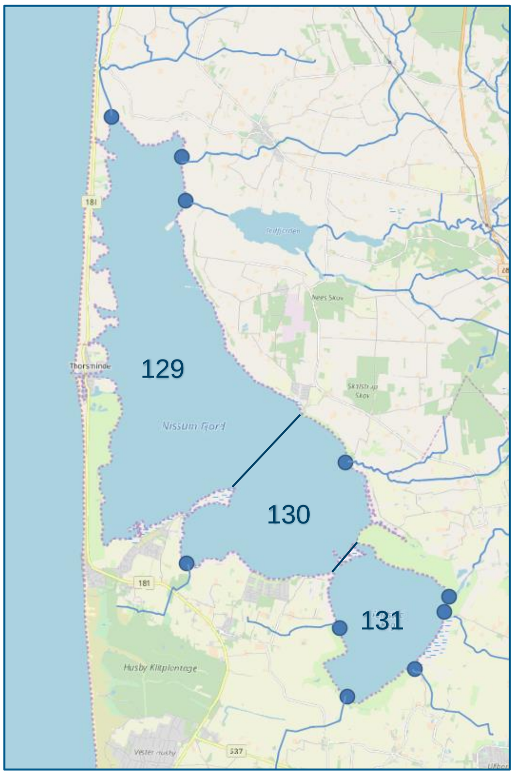


Figure 4.4 Location of freshwater sources and subdivision of Nissum Fjord into three water bodies (129, 130, 131), for which total daily discharge time series were distributed to the sources.

4.3.4 Sluice Flow

The water exchange between Nissum Fjord and the sea is controlled through a sluice located at Thorsminde in the central-western part of the fjord. In this model the sea-fjord water exchange was modelled using point sources for in- and outflow.

It was not possible to obtain operational data regarding the sluice. Therefore, an estimation of the discharge between the sea and the fjord was carried out based on the volumetric water difference in the fjord over time, expressed by the equation:

$$\frac{\Delta V}{\Delta t} = Q_{land} + Q_{net\_prec} + Q_{sea}$$

where V is the water volume in the fjord, t is time, Q_{land} is the freshwater discharge from land, Q_{net_prec} is the net precipitation (precipitation minus evaporation) and Q_{sea} is the discharge to and from the sea through the sluice. Freshwater data were taken from the sources mentioned in section 4.3.3 and precipitation from the forcings mentioned in section 4.3.2, while evaporation rates were computed by the model.

The volumetric change in fjord water was estimated by the fjord surface area and water level measurements which were conducted by the Danish Coastal Authority at three locations around the fjord, see Figure 4.5. Machine learning algorithms were used to fill in missing data in the water level time series. The predictability of the machine learning was highly accurate due to availability of large datasets of water levels, freshwater discharge and wind fields. Figure 4.6 shows an example of filled in missing data for the water level time series measured at Skovlund.

Figure 4.5 Points showing the location of water level measurements conducted by the Danish Coastal Authority.

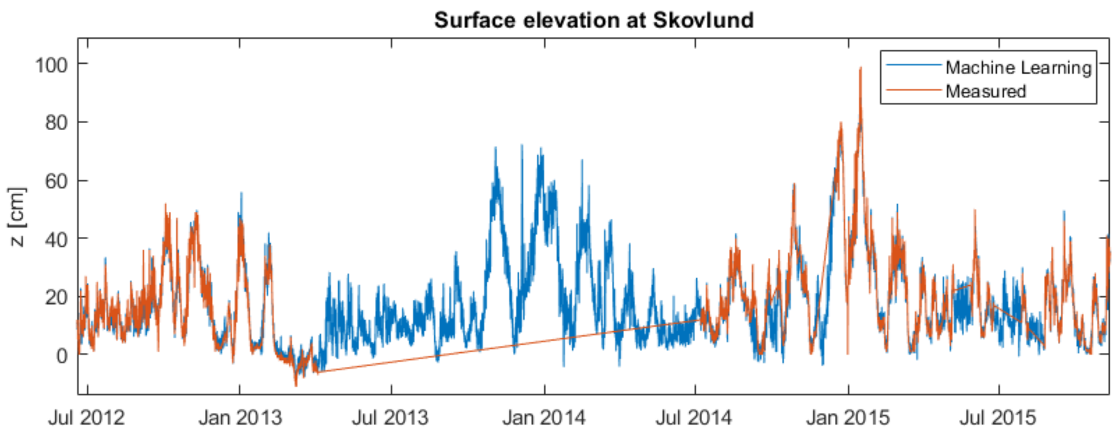


Figure 4.6 Gap in water level measurement at Skovlund, filled with machine learning regression.

The three water level time series were averaged to estimate a mean water level, which was then filtered with a lowpass filter of 12 hours to dampen excessively large fluctuations. The choice of 12 hours appeared to give the best correlation between the water volume time series and the difference between the water level in the sea and the fjord. It also yielded the most realistic Q_{sea} discharge values when comparing with information obtained about sluice practice.

The Q_{sea} discharge shows a positive sign when sea water flows into the fjord and a negative sign when fjord water flows out to the sea. In the model this was subdivided into several in- and outflow sources that were distributed in the proximity of the sluice, as seen in Figure 4.7. The salinity and temperature of the inflow sources were set by a time series created from measurements in the nearby open sea. On the other hand, the outflow sources removed the existing salt and temperature in their respective mesh cells. The sources were also distributed vertically through the sigma-layers, to imitate a realistic distribution through the water column. For the outflow sources this meant that the sources were placed in the upper part of the water column, while the inflow sources were placed close to the fjord bed to represent the denser sea water.

Figure 4.7 Location of sluice sources in Thorsminde. The red point represents five outflow sources, which were placed in sigma-layers 4-8. Each green point represents one or two inflow sources which were placed in the sigma-layers 1-2.

4.4 Initial Conditions

4.4.1 Introduction

To properly initiate a model simulation, the model requires initial conditions for the various state variables. For the hydrodynamic model the state variables comprise water level, current, salinity and water temperature.

4.4.2 Initial Water Level and Current Conditions

The normal procedure for water level and current is to apply a so-called 'cold start'. This means that the water is stagnant with no currents initially. Immediately after starting the simulation the water begins to move under the influence of the model forcings, and after a short time (~1day) the model has 'warmed up'.

4.4.3 Salinity and Water Temperature

Contrary to water level and current the warm-up time for salinity and water temperature is typically long (months or years), which is not useful. Consequently, 3D fields of salinity and water temperature at the simulation start time are prepared and applied as initial conditions for the simulation. These fields are typically established based on results from an encompassing (larger) model or based on local monitoring data.

In the present case the applied salinity and water temperature initial fields are based on a weighted average of salinity and temperature measurements from six stations (RKB21, RKB22, RKB23, RKB24, RKB25 and RKB26). The model is then run for the last three months of 2001, so that correct initial fields are established by 1 January 2002.

5 Model Calibration

5.1 Introduction

Having set up the model, the model calibration is undertaken. The model calibration is the process of adjusting model settings and model constants in order to obtain satisfactory agreement between observations and model results. In practice the model setup and the model calibration are often performed iteratively, since a good comparison between observations and model results requires a well-proportioned model domain as well as adequate model forcings, and this is not always obtained in the first attempt.

5.2 Model Settings

In Table 5.1 a summary of applied model settings and constants is given.

Table 5.1 Summary of applied hydrodynamic model settings and constants in the Ringkøbing fjord model.

Feature/Parameter	Setting/Value
Flooding and drying	Included with parameters: 0.005m, 0.05m and 0.1m
Wind friction coefficient	Linearly varying between 0.001255 and 0.002425 for wind speeds between 7 and 25m/s
Bed roughness	Constant 0.05m
Eddy viscosity	Horizontally: Smagorinsky formulation, C_s=0.28 Vertically: k-ε model with standard parameters and no damping
Solution technique	Shallow water equations: Low order Transport equations: High order
Overall time-step	30s
Heat exchange	Standard parameters
Dispersion (S/T)	Scaled to Eddy viscosity. Horizontal/vertical scaling factors = 0.1/0.01

6 Model Validation

6.1 Introduction

The model validation is the process of comparing observations and model results qualitatively and quantitatively to demonstrate the suitability of the model. The qualitative comparison is typically done graphically, and the quantitative comparison is typically done by means of certain performance (goodness of fit) measures. As such the model validation constitutes the documentation of the model performance.

The Nissum Fjord model was run for the period 2002-2016, but the validation period was defined as the 6-year period 2011-2016. Consequently, model comparison plots and performance measures are presented for this period, whereas model results and measurements of salinity and temperature are presented for the entire period using a WEB-tool (rbmp2021-2027.dhigroup.com).

Figure 6.1 shows the different locations with salinity and temperature (ST) measurements during the period 2002-2016. These data are presented using the WEB-tool. For the validation period (2011-2016) the stations RKB22 and RKB24 had sufficient data to be included in the model validation.

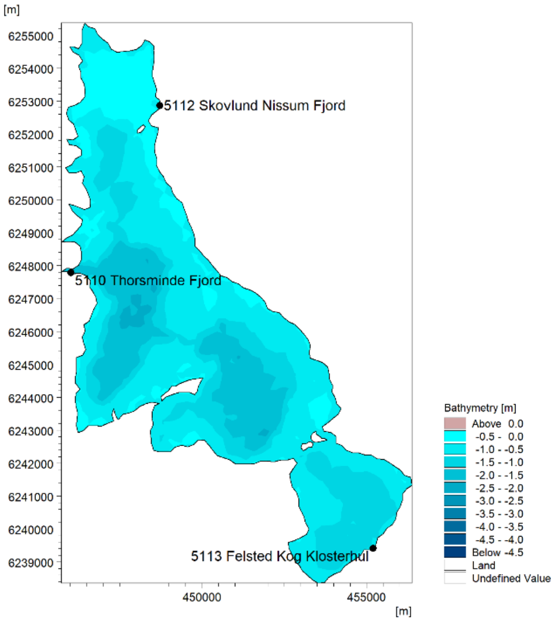


Figure 6.1 Location of the validation stations for salinity and temperature (left) and water level (right) used in the model validation.

6.2 Performance Measures

6.2.1 Water Level

Comparison of modelled and measured water level at Felsted Kog (Figure 6.2) shows a fine match, representing the tidal and non-tidal variability of the water level.

A statistical comparison of the modelled and measured water level was carried out resulting in a high correlation coefficient (CC) of 0.96 (100% fit would have resulted in CC=1), Figure 6.3.

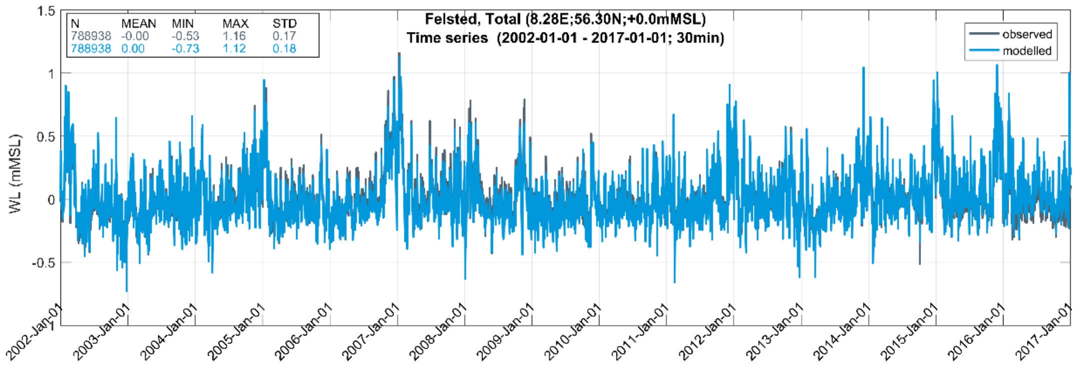


Figure 6.2 Modelled surface elevation (light blue line) compared to measured data (dark blue line) at Felsted Kog.

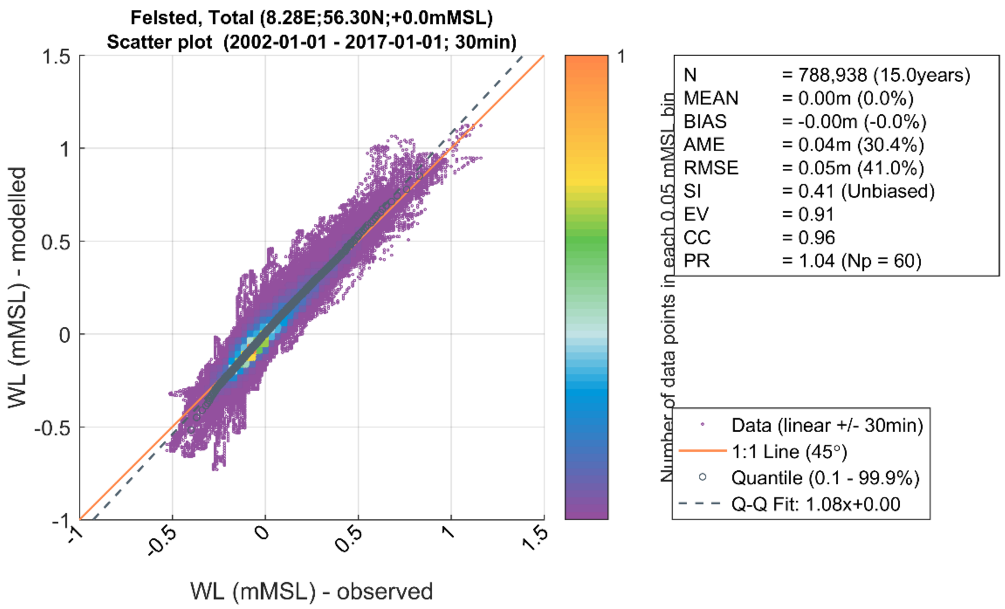


Figure 6.3 Statistical analysis of modelled surface elevation and measured data at Felsted Kog

Similar quality water level comparisons were obtained at the two remaining measurement stations.

6.2.2 Salinity and Water Temperature

Figure 6.4 shows an example of comparison of modelled and measured salinity at station RKB22 (Figure 6.1). The model reproduces well the limited salinity stratification of the water column as well as the seasonality throughout the year.

Figure 6.5 shows a comparison of modelled and measured temperature at the same station. The model reproduces correctly the limited thermal stratification of the water column and the seasonal variation observed in the measured data.

Further the figures illustrate that also interannual variations in the two parameters are represented by the model.

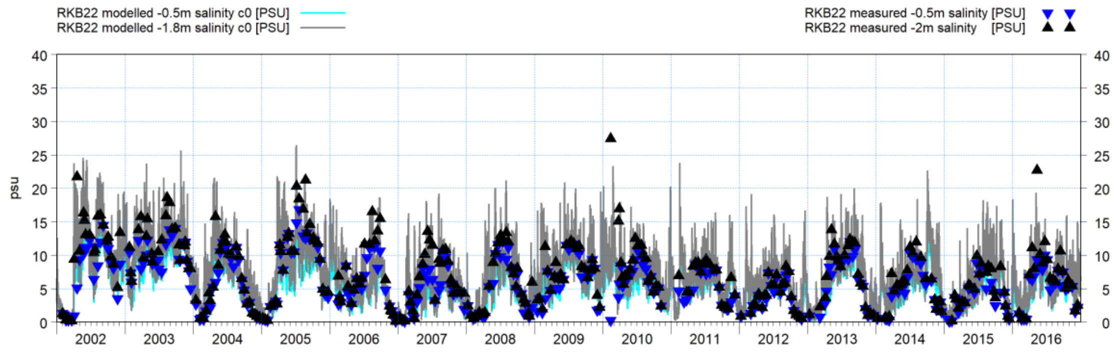


Figure 6.4 Surface and bottom (light blue and grey lines) modelled salinity at station RKB22 compared to measured surface and bottom (blue and black triangles) values.

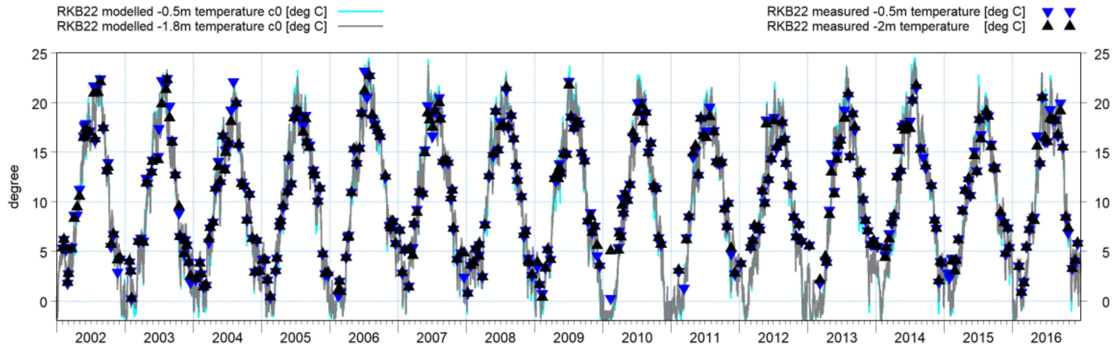


Figure 6.5 Surface and bottom (light blue and grey lines) modelled temperature at station RKB22 compared to measured surface and bottom (blue and black triangles) values.

In Table 6.1 and Table 6.2 the model performance is evaluated according to DHI (2019a) based on three performance measures: P-Bias, Spearman Rank Correlation and Modelling Efficiency Factor. Representative stations with good coverage available for the period 2011-2016 are included and the entire station network in the Nissum Fjord model domain is shown in Figure 6.1. In the tables color codes are included to highlight the overall model performance as 'excellent', 'very good', 'good' or 'poor'.

For the hydrodynamic model covering Nissum Fjord we aim at 'excellent' or 'very good' model performance at more than 3 out of 4 measurement stations. For salinity the model performance was evaluated against the three different quality measures at two stations, and according to Table 6.1 the model meets 'excellent' or 'very good' at both stations for P-Bias and the Spearman Rank Correlation, whereas the model performance meets 'good' for the Modelling Efficiency Factor. For water temperature (see Table 6.2) the model meets 'excellent' at both stations for all measures.

Here, we conclude that the hydrodynamic model covering Nissum Fjord is well suited for continued biogeochemical model development as part of the overall development of mechanistic models towards the RBMP 2021-2027.

Table 6.1 Review of model performance based on measured and modelled salinities for the validation period 2011-2016. The performance is evaluated according to DHI (2019a) and blue colour indicates an 'excellent' model, dark green indicates a 'very good' model, light green indicates a 'good' model and yellow indicates a 'poor' model.

Station	P-Bias (%)	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
RKB22	0.7	0.72	0.44	268
RKB24	-3.6	0.75	0.43	160

Table 6.2 Review of model performance based on measured and modelled water temperatures for the validation period 2011-2016. The performance is evaluated according to DHI (2019a) and blue colour indicates an 'excellent' model, dark green indicates a 'very good' model, light green indicates a 'good' model and yellow indicates a 'poor' model.

Station	P-Bias (%)	Spearman Rank Correlation	Modelling Efficiency Factor	Number of observations
RKB22	-7.6	0.98	0.90	268
RKB24	-6.1	0.97	0.89	160

7 References

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